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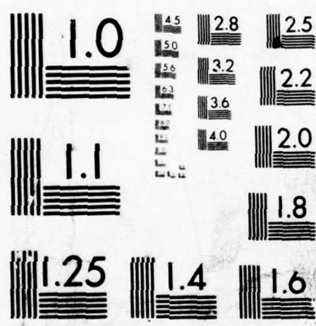

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

→ The status of underwater heat sources being developed for U.S. Navy divers is reported. Specific heater types are propane catalytic combustion heaters, seawater hydraulic heaters, and magnesium-oxygen combustion heaters. Portable underwater energy source concepts are reviewed. The review is limited to theoretical figures regarding size and heat output. Principles of operation, hardware design, engineering prototype test results, and heater interfacing with the diver are described for the specific heaters being developed for the Navy.

20.

From the overall theoretical predictions and actual performance data of the various underwater heater concepts, it is concluded that new diver heater concepts presently under investigation by the Navy will enhance the mission capabilities of the Fleet diver. Furthermore, these concepts may be readily adaptable for commercial application and could solve diver thermal protection problems associated with commercial diving in cold water.

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INTRODUCTION

In the past, diving missions have been limited to a certain extent by breathing gas duration, carbon dioxide scrubbing capability, depth, distance to be traveled, and decompression constraints. Through research and development, the limitations in these areas have been reduced so that diver thermal protection has become one of the single most limiting factors in Navy diving missions. NCSC has evaluated potential heating techniques and devices relative to diver missions and applications to determine the course of action the Navy should follow in diver heater research and development. This report summarizes the characteristics of various potential heat sources for underwater applications, and reviews the results of past and present efforts in Navy diver heater development.

DIVER THERMAL REQUIREMENTS

Before considering a supplemental heat source, the diver thermal requirements must first be established for determining the amount of supplemental heating, if any, required for a given diving mission. Generally, if a mission can possibly be performed without supplemental heating, it is more economical and practical to depend on the garment insulation alone to keep the diver warm by retaining body heat. If the garment insulation is not sufficient, it may be more practical to use two or more shifts of divers to accomplish the mission. If it is not practical to use more than one team of divers or if the mission conditions are extremely severe, supplemental heating may be the only way to successfully accomplish the mission.

To determine the diver's ability to perform an assigned task, the mission conditions must be known; specifically, (1) water temperature, (2) water depth, (3) breathing gas, (4) diver work rate, and (5) diver dress; all play a key role in determining a diver's performance on an assigned job. Once these parameters are known, an estimate can be made of the expected duration of effective work by the diver. Tables 1 and 2 give minimum durations which might be expected from a typical diver for various conditions without supplemental heat. Table 1 give results for a diver working in shallow water while breathing air, and Table 2 gives results for a diver working deeper than 61 metres and breathing heliox.

(Text Continued on Page 3)

TABLE 1

TYPICAL DIVER WORK CAPABILITY BREATHING AIR IN COLD WATER

Diver Dress	Water Temperature (C)	Effective Duration (Minutes: 100 kcal/Hr Work Rate, Surface	100 kcal/Hr Work Rate, Metres	300 kcal/Hr Work Rate, Surface	300 kcal/Hr Work Rate, Metres
1/4" foam wet suit	0	30-45	15	60	15
	5	60	15	240	30
	10	90	30	NL*	60
	20	NL	120	NL	NL
1/4" foam suit with nylon pile underwear	0	75	30	NL	60
	5	90	60	NL	180
	10	120	90	NL	NL
	20	NL	N1	NL	NL

*NL - Mission is not limited by cold water exposure

TABLE 2

TYPICAL DIVER WORK CAPABILITY BREATHING HELIOX IN COLD WATER DEEPER THAN 61 METRES

Diver Dress	Water Temperature (C)	Effective Duration (Minutes): 100 kcal/Hr Work Rate	300 kcal/Hr Work Rate
1/4" foam wet suit	0	15	15
	5	15	15
	10	30	30
	20	90	NL*
1/4" foam dry suit with nylon pile underwear	0	15	15
	5	30	30
	10	45	60
	20	90	NL

*NL - Mission is not limited by cold water exposure.

It should be emphasized that these tables represent only typical values for effective performance based on a maximum allowed heat loss by the diver of 200 kcal according to BUMED criteria developed under contract through the Office of Naval Research[1]. These durations are quite conservative values and are based on the diver's performance at optimum efficiency.

If the mission requirements are known, they can be compared with effective duration values such as those given in Tables 1 and 2 to determine if the job should be done with a single dive team with no supplemental heat, more than one dive team in shifts without supplemental heat, or a single dive team with supplemental heat. If supplemental heat is desirable, there are numerous potential heat sources which may have application depending on the mission requirements.

POTENTIAL UNDERWATER HEAT SOURCES

There are primarily two distinct classifications of underwater heat sources—surface supported heaters and portable heaters which may be operated without surface support. The surface supported heat sources generally have the energy source on a surface vessel and the energy produced at the surface is converted to heat before reaching the diver. For these heat sources, the energy available is not limited to maximum output or duration within reasonable constraints. The more portable heat sources not requiring surface support may be diver-carried or mounted on a submerged vehicle such as a personnel transfer capsule (PTC). These heat sources are limited in the amount of energy and maximum heat output they can produce since the fuel and oxidizer, if required, must be carried by the diver or submerged vehicle. They are further constrained as to overall size, weight, and geometry.

SURFACE SUPPORTED HEATER SYSTEMS

The surface supported heat sources are more suitable than portable heat sources for most working dive assignments. They are simpler, more rugged, and more dependable than portable heat sources. There have been significant developmental efforts in surface supported heating systems

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[1] Webb, P. and Beckman, E. L., et al., *Proposed Thermal Limits for Divers: A Guide for Designers of Thermally Protective Equipment*, (ONR Contract N00014-72-C-0057) July 1976.

and they have seen widespread commercial and Navy applications. Portable heat sources, on the other hand, have been non-existent in diving applications although their continued development does make them competitive with surface supported heating systems in certain applications. However, the surface supported heating systems will continue to remain the cold water companion for most working dives.

There are numerous techniques for heating a diver from the surface. Table 3 describes some proven and some promising methods. Surface supplied hot water and surface supplied electrical heating are available commercially with details available from the manufacturers. The Navy is involved in the development of hydraulic, pneumatic, and chemical methods of surface supported heating and these techniques are discussed in detail under Navy Underwater Heater Development Efforts.

PORTABLE HEATER SYSTEMS

Portable heat sources are being developed for situations more unique than those presented by most working dives. These sources could be used where it is not feasible to have a support vessel large enough to carry a surface supported heating system and/or surface supported diving system. They could be used as emergency standby systems in the event that the surface supported heater fails for a short period. They could be used in applications where the presence of surface vessels is impractical. In short, the portable heat sources will supplement the surface heaters and provide diver heating in the more rare instances where surface support is not available, feasible, or desirable.

There are several important areas to be considered for portable heat sources in an underwater application: (1) thermal output, (2) duration, (3) weight and volume, (4) range of control, (5) simplicity of operation, (6) reliability, (7) maintainability, (8) operational cost, and (9) safety. Next to safety, the most important considerations for portable heat sources are thermal output, duration, weight, and volume.

A portable underwater heater system should produce the necessary thermal output for the maximum anticipated time, from the smallest possible package to provide the diver or vehicle maximum mobility and utilization of space. The overall size of most portable heater systems is determined by the fuel and oxidizer requirements established by the thermal requirements for the intended mission. Therefore, to optimize heater design, fuels and oxidizers must be chosen which produce a high heat output per unit weight for high density materials such as solids and liquids or a high heat output per unit volume for low density (gases) fuels and oxidizers. Table 4, which was constructed primarily from

(Text Continued on Page 8)

TABLE 3

SURFACE SUPPORTED HEAT SOURCES

Heat Source	Description	Status	Contacts
1. Hot water	Water is heated at the surface and pumped to the diver where it is circulated over the diver's body through some type of hot water circulation garment. The hot water may also be circulated through a breath heater to heat the diver's breathing gas.	Commercially available	Heater—DUI, Kinergetics Hot water suits-DUI
2. Electrical	a. Electrical power is sent to the diver from the surface and used to heat the diver through resistance heating using an electrical resistance underwear garment.	Commerically available	La Spirothechnique
	b. Electrical power is used to operate a "lossy" electrical motor-pump combination where the losses from the motor-pump appear as heat used to warm the water, which in turn warms the diver using a hot water circulation garment.	Commercially available	Divermatics
3. Hydraulic	High pressure water is pumped to the diver where the fluid power is converted to friction thereby heating water which warms the diver using a hot water circulation garment.	Developmental (engineering prototype stage)	NCSC Westinghouse
4. Pneumatic	High pressure air is passed through a vortex tube which converts the stored energy in the inlet gas into a hot air stream and a cold air stream. The cold air stream is exhausted to ambient and the warm air stream is used to heat the diver by warming his dry suit.	Developmental (concept feasibility stage)	NCSC Vortex Corp.
5. Chemical	Air and hydrocarbons such as propane are pumped to the diver where they are allowed to combust catalytically in a reaction chamber-heat exchanger that heats water which is circulated through a heat distribution garment worn by the diver.	Developmental (engineering prototype stage)	NCSC Energy Systems Corp.

TABLE 4

ENERGY PRODUCTION OF VARIOUS POTENTIAL HEAT SOURCES
(Sheet 1 of 2)

Classification	Reaction	Theoretical Energy Production (Watt-Hours/kg Reactants*)
1. Electrical (Battery)	Magnesium-iron-seawater	4080*
	Sodium-oxygen	2230
	Lithium chloride (experimental)	2205
	Lithium fluoride (experimental)	1655
	Zinc-air	880
	Sodium-sulfur (experimental)	770
	Magnesium bromide (experimental)	550
	Silver oxide-zinc (silver cell)	445
	Manganese dioxide-zinc (dry cell)	285
	Mercury oxide-zinc (mercury cell)	230
	Nickel-cadmium	210
	Magnesium-silver chloride (torpedo battery)	200
	Lead-acid (secondary storage battery)	165
2. Chemical Combustion (hydrocarbons)	$H_2 + O_2$	4410
	Methane + O_2	3090
	Ethane + O_2	3040
	Propane + O_2	3020
	Fuel oil + liquid O_2	3020
	Butane + O_2	3000
	Fuel oil + 90% H_2O_2	3140
Combustion (Metals)	$2Be + O_2 \rightarrow 2\ BeO$	6660
	$2Li + F_2 \rightarrow 2\ LiF$	6550
	$4Li + O_2 \rightarrow 2Li_2O$	5535
	$4B + 3\ O_2 \rightarrow 2B_2O_3$	5480
	$4Al + 3\ O_2 \rightarrow 2Al_2O_3$	4565
	$2Mg + O_2 \rightarrow 2MgO$	4210
	$2Na + F_2 \rightarrow 2NaF$	3750
	$4P + 5\ O_2 \rightarrow 2P_2O_5$	2955
	$2K + F_2 \rightarrow 2KF$	2690
	$2Li + Cl_2 \rightarrow 2LiCl$	2670
	$Zr + O_2 \rightarrow ZrO_2$	2450
	$4Na + O_2 \rightarrow 2Na_2O$	1875
	$Fe + O \rightarrow FeO$	1510
Heat of Decomposition	Hydrazine hydrate	3350

*For those reactions in which seawater is a reactant, the weight consideration of the seawater has not been included in these values.

TABLE 4

(Sheet 2 of 2)

Classification	Reaction	Theoretical Energy Production (Watt-Hours/kg Reactants*)
Inorganic Hydrolysis		
	$Li_3N(s) + 3H_2O(l) \rightarrow 3LiOH(aq) + NH_3(aq)$	4410*
	$Mg_3N(s) = 6H_1O(l) \rightarrow$ [illegible] $3Mg(OH)_2\ (s) + 2NH_2\ (aq)$	2095&
	$Mg_3N(s) = 6H_1O(l)$ T $3Mg(OH)_2\ (s) + 2NH_2\ (aq)$	2095*
	$AlN(s) + 3H_2O(l)$ T $Al(OH)_3\ (s) + NH_3\ (aq)$	

TABLE 4

(Sheet 2 of 2)

Classification	Reaction	Theoretical Energy Production (Watt-Hours/kg Reactants*)
Inorganic Hydrolysis		
	$Li_3N(s) + 3H_2O(l) \rightarrow 3LiOH(aq) + NH_3(aq)$	4410*
	$Mg_3N(s) = 6H_1O(l) \rightarrow 3Mg(OH)_2\ (s) + 2NH_3\ (aq)$	2095*
	$AlN(s) + 3H_2O(l) \rightarrow Al(OH)_3\ (s) + NH_3\ (aq)$	1255*
	$CaO(s) + H_2O(l) \rightarrow Ca(OH)_2\ (s)$	330*
	$MgO(s) + H_2O(l) \rightarrow Mg(OH)_2\ (s)$	265*
Organic Hydrolysis	Ketene + water → ethylene glycol	925*
	Cyanimide + water → ammonium carbonate	835*
	Ethylene oxide + water → ehtylene glycol	440*
	Succinic anhydride + water → succinic (Butanedioc) acid	395*
Hydration	$AlCl_3(s) + 6H_2O(l) \rightarrow AlCl_3 \cdot 6H_2O(s)$	575*
	$MgCl_2(s) + 6H_2O(l) \rightarrow MgCl_2 \cdot 6H_2O(s)$	440*
	$MgClO_4(s) + 6H_2O(l) \rightarrow MgClO_4 \cdot 6H_2O(s)$	330*
	$B_2O_3(s) + 3H_2O(l) \rightarrow B_2O_3 \cdot 3H_2O(s)$	310*
	$MgSO_4(s) + 7H_2O(l) \rightarrow MgSO_4 \cdot 7H_2O(s)$	265*
	$CaCl_2(s) + 6H_2O(l) \rightarrow CaCl_2 \cdot 6H_2O(s)$	240*
Chemical Acid-base Neutralization		
	Succinic anhydride + ammonia → ammonium succinamate	465
	Lithium hydroxide + hydrochloric acid → lithium chloride + water	330
	Acetic anhydride + ammonia → acetamide + ammonium acetate	310
	Oxalic acid + ammonia → acetamide + ammonium acetate	265
	Acetic acid + ammonia → Ammonium acetate	265
Gel Forming Systems		
	Magnesium nitride + acrylic acid + water → magnesium hydroxide + ammonium acrylate	1875*
	Magnesium nitride + acrylic acid → water + magnesium acrylate + ammonium acrylate	1455
	Lithium nitride + water → lithium hydroxide + ammonia) Lithium hydroxide + acrylic acid → water + lithium acrylate (gel)) Ammonia + acrylic acid → water + ammonium acrylate (gel))	1210*
3. Latent Heat	Sensible heat and) Lithium hydride	1875
	Change of state) Lithium fluoride	305
	Sensible heat Boron	290
4. Nuclear	Plutonium 238 → α	240 (actual incl. shielding and hardware)

*For those reactions in which seawater is a reactant, the weight consideration of the seawater has not been included in these values.

information reported in References 2 and 3, gives a comparison of the energy production per unit weight of reactants for various potential heat sources. Table 5 lists the information in Table 4 according to the types of reactions in order of priority. The volume requirements and other pertinent details are discussed below for the reactions listed in Table 5.

TABLE 5

LIST OF ENERGY PRODUCING REACTIONS
IN ORDER OF PRIORITY

Reaction	Potential energy (Watt-Hours/kg Reactants)
1. Combustion (metals)	1800 - 6700
2. Combustion (hydrocarbons)	2000 - 4500
3. Inorganic hydrolysis	300 - 4500
4. Batteries	150 - 4100
5. Heat of decomposition	≈ 3300
6. Gel-forming systems	1200 - 1900
7. Latent heat	300 - 1900
8. Organic hydrolysis	400 - 900
9. Hydration	250 - 600
10. Acid-base neutralization	250 - 450
11. Nuclear	≈ 450

In order to compare the different heat sources, a base line value for total energy output must be established. For that purpose, a base line value of 3000 watt-hours will be used in the discussions. This could be a power output of 500 watts for 6 hours or 1000 watts for 3 hours. A heating value of 500-1000 watts is considered reasonable for keeping a diver warm in the most extreme climates, provided he is wearing a dry suit and suitable underwear with a closed-circuit hot water distribution garment beneath the dry suit.

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(2) Civil Engineering Laboratory Tech Note N-1501, *A Self-Contained Experimental Diver Heater*, by S. A. Black and S. S. Sergev, September 1977.

(3) Naval Surface Weapons Center, *Thermal Energy Sources for Subsea Diving Operations, An Informal Presentation of Preliminary Conceptual Approaches for Consideration*, TRW for D. C. von Adlerhoch.

Combustion (Metals)

The combustion of metals offers the highest heating values of all sources considered. Table 6 shows the weights and volumes of fuels and oxidizers for a 3 kW-hour mission. As can be seen from Table 6, the fluorine combustion reactions require a considerable volume for the fluorine. This excessive volume, coupled with the toxicity hazards of fluorine, make these reactions undesirable for underwater heat sources. Likewise, the hazards of chlorine present a strong case for omitting these reactions from consideration. The oxidizer requirements for

TABLE 6

METAL, FUEL, AND OXIDIZER REQUIREMENTS
FOR A 3 KW-HOUR MISSION

Combustion Product	Fuel Weight (kg)	Fuel Volume* (cm^3)	Oxidizer Weight (kg)	Oxidizer Volume** (cm^3)
Al_2O_3	0.35	127	0.31	1137
B_2O_3	0.17	74	0.38	1388
BeO	0.16	88	0.29	1086
P_2O_5	0.44	202	0.57	2107
Na_2O	0.41	424	1.19	4382
MgO	0.43	239	0.28	1037
Li_2O	0.25	477	0.29	1070
LiF	0.12	229	0.34	9988
LiCl	0.19	349	0.94	667
NaF	0.44	449	0.37	10933
ZrO_2	0.91	134	0.32	1170
KF	0.75	873	0.36	10797
FeO	1.54	198	0.44	1639

*These volumes are based on the density of a solid fuel. For a powdered fuel such as shavings or a metal wool, the fuel volumes may be significantly greater depending on fineness of the material. Shavings or metal wool are desirable from an ignition standpoint and combustion is easier to maintain. A tradeoff is necessary with density to minimize volume and maximize performance.

**These oxidizer volumes are based on a storage pressure of 205 atmospheres (3000 psi) for the oxygen and standard DOT shipping v alues for chlorine and fluorine.

sodium are also excessive when compared with some of the other reactions. Ordinary phosphorous burns spontaneously in air and is very poisonous; white phosphorous is extremely reactive in air and may cause severe skin burns on contact; red phosphorous is fairly stable but does emit toxic fumes of the oxidizer upon heating—all good reasons for excluding phosphorous as an underwater heat source. Beryllium, which costs about $150 per kilogram, has an ignition temperature in excess of 2200°C which may create some problems in starting and sustaining combustion of this metal. There remain aluminum, boron, iron, lithium, magnesiusm, and zirconium. These materials are discussed further in Navy Underwater Heater Development Efforts.

Combustion (Hydrocarbons)

Most of the hydrocarbon combustion reactions produce approximately the same amount of heat, approximately 3000 watt-hours per kilogram of reactant. Hydrogen is included in this category and, while it produces 50 percent more power on a per weight of reactants basis, the added weight required to store the gaseous hydrogen in pressurized vessels or as a metal hydride tends to offset this advantage. The weight required to store gaseous oxygen for burning hydrocarbons is also significant. To date, efforts to burn hydrocarbons with pure oxygen in stoichiometric proportions have been unsuccessful in that spontaneous combustion occurs rather than the desired controlled catalytic combustion necessary for safe diver heating. For this reason, air has been used as an oxidizer and, while the reaction is a controlled catalytic reaction, five times the amount of gas is required to produce the equivalent amount of heat that could be obtained if pure oxygen were used. There may be an additional problem in using propane, ethane, and butane, since they are normally stored under their own vapor pressure at ambient temperature. This may limit, to some degree, the depth of seawater at which they can be used. Methane, on the other hand, is shipped as a non-liquified gas at high pressure which means a higher storage volume requirement. The heating value for fuel oil and hydrogen peroxide is significantly less than that of other hydrocarbons, and the cryogenic requirements for storing liquid oxygen as an oxidizer for fuel oil make these two methods of heat production unattractive. Table 7 gives the weight and volume requirements for using some of the more promising hydrocarbons as underwater heat sources for a 3 kW-hour mission. Of those listed, the Navy has investigated propane and hydrogen in prototype diver heater applications.

Inorganic Hydrolysis

The inorganic hydrolysis reactions are attractive because they do not require storing an oxidizing gas as do the metallic and hydrocarbon combustion reactions. These reactions require water instead of an oxidizer and there is plenty of seawater available. There has been little work done to date towards utilizing these reactions for underwater heat

(Text Continued on Page 12)

TABLE 7

HYDROCARBON FUEL AND OXIDIZER REQUIREMENTS
FOR A 3 KW-HOUR MISSION

Fuel	Fuel Weight (kg)	Fuel Volume (cm^3)	Fuel Vapor Pressure @21.1°C (atm)	Oxidizer Requirements			
				Air Weight (kg)	Air Volume (cm^3)	O_2 Weight (kg)	O_2 Volume (cm^3)
Butane	0.22	375	2.18	3.36	13,600	0.78***	2870
Ethane	0.21	600	38.10	3.35	13,550	0.78	2860
Methane	0.20	1860	NA**	3.36	13,600	0.78	2870
Propane	0.21	425	8.16	3.33	13,500	0.77	2845
Hydrogen	0.08	4500/4750*	NA	2.58	10,490	0.60	2220

*4500 cm^3 would be required to store 0.08 kilograms of hydrogen under high pressure at 205 atmospheres. Billings Energy Corporation manufactures a container for storing hydrogen as a metal hydride which will store 0.23 kilograms of hydrogen within 4750 cm^3 at a pressure of 35 atmospheres. Cylinder weight is 18.6 kilograms.

**Methane is shipped as a non-liquified gas at 155 atmospheres.

***To date, efforts to burn hydrocarbons such as butane, ethane, methane, and propane catalytically in pure oxygen have been unsuccessful.

production. The Navy did investigate the use of calcium chloride for diver heating back in the mid-1960's, but there has not been any follow-on work done to date. The heat of solution for calcium chloride is 180 watt-hours per kilogram which is considerably less than that of the inorganic hydrolysis reactions listed in Table 4. There are certain trade-offs to be considered for the inorganic hydrolysis reactions. For the hydrolysis of MgO or CaO, much more fuel must be used than for the hydrolysis of the nitrides of aluminum, magnesium, or lithium. For instance, on a 3 kW-hour mission, 11.3 kilograms of MgO or 9.1 kilograms of CaO is required, whereas only 2.4 kilograms of AlN, 1.4 kilograms of Mg_3N_2 or 0.7 kilograms of Li_3N would be required. On a cost basis, however, the MgO would cost approximately $65, CaO - $85, Al_3N - $1100, Mg_3N_2 - $400, and Li_3N - $650. This means that if a smaller volume and weight of fuel is used, a significantly higher cost is incurred. To determine other pertinent data such as rates of reaction, controllability, and safety, more research and development is necessary on inorganic hydrolysis reactions.

Batteries

There are two different modes of heating using batteries as portable heat sources. The electrical energy can be converted to heat through the use of electrical resistance-wire underwear worn by the diver, or the battery can be short-circuited internally and a water-to-electrolyte heat exchanger can be used to heat water passing through a hot water distribution garment worn by the diver. This second technique has been developed by the Navy using a magnesium-iron-seawater battery with good success. As a result of that development, commercial units are not available from Sea Systems Development, P. O. Box 101, Port Hueneme, California; or Kinergetics, Incorporated, 6029 Reseda Boulevard, Tarzana, California. The heat output from these heaters is significantly greater than can be obtained using the other batteries in the more conventional mode using resistance-wire underwear. More details on the magnesium-iron-seawater heaters and electrical resistance wire underwear are given under Navy Underwater Heater Development Efforts.

Heat of Decomposition

The decomposition of hydrazine hydrate produces a significant amount of heat per unit weight. Only theoretical work has been done towards developing a technique using this heat source for underwater applications, hence, little is known of the problem areas. Both hydrazine and hydrazine hydrate are violent poisons and cause strong caustic actions on the skin. They can also cause injury to the liver and blood. The handling and safety problems, are therefore, undesirable but can and have been overcome in other applications. A hydrazine-fueled diver's heating system has been patented by Mr. John J. Bayles of the Naval Civil Engineering Laboratory, Port Hueneme, California. This work was conducted

several years ago and was limited to feasibility studies and preliminary design work.

Gel-Forming Systems

The reaction of magnesium nitride with acrylic acid and water appears to be the more promising heat source of the gel-forming reactions from both a cost and heat output standpoint. The current cost for magnesium nitride is approximately $285 per kilogram compared to $880 per kilogram for lithium nitride. For the lithium nitride reaction, 0.3 kilograms of lithium nitride would be required for a 3 kW-hour mission, while for the magnesium nitride-acrylic acid-water reaction, 0.7 kilograms of magnesium nitride would be required. These costs would come down for large quantities and extensive use.

Latent Heat

This approach is different from the previously discussed reactions in that this represents a physical process instead of a chemical reaction. In this technique, a material which has a high heat storage capacity per unit weight and per unit volume is used to store heat from a heat source at the surface to be used later by the diver on his mission. Sanders Nuclear Corporation proposed a diver heater based on this principle in the late 1960's and the technique was also investigated at NCSC in 1972. Problem areas are insulation and overall system weight. Heat losses must be minimized to keep the overall system weight from being impractical.

Organic Hydrolysis

These reactions, like the inorganic hydrolysis reactions, are attractive because all that is needed to react with the fuel is seawater. Additional research and development is required to determine the feasibility of using these reactions for underwater heat sources.

Hydration

Like the hydrolysis reactions, the hydration reactions require only seawater to react with the fuel, thereby minimizing the system volume requirements. Additional studies are required to determine if the hydrolysis or hydration reactions are more feasible than other techniques for underwater heat production.

Acid-Base Neutralization

These reactions appear marginal for use as underwater heat sources due to the large weight requirements.

Nuclear

Mound Laboratory of Miamisburg, Ohio, developed a diver's isotopic swimsuit heater during 1967-68 for potential use in the Navy's SEALAB III experiment. At that time, a Wellson tube suit was used to circulate the heated water over the diver's body with wet suits being worn over the tube suit. In this configuration, the heater did not produce sufficient heat to warm the diver. If a dry suit were worn over the tube suit, this heater would perform much better. However, the overall weight and volume requirements for the nuclear heater systems are excessive for further consideration as underwater heat sources.

NAVY UNDERWATER HEATER DEVELOPMENT EFFORTS

The United States Navy began major development of underwater heat sources during the SEALAB experiments of the late 1960's. The development has included in-house and contract work in both past and current ongoing efforts. These efforts had limited success but, with each technique tried, more information was gathered on what would and would not work, what was needed, and what major problem areas existed so that the current efforts had a strong data base from which to proceed.

ELECTRICAL

One of the first heating concepts investigated by the Navy was an electrically heated, pressure-compensated wet suit for SEALAB II in 1965[(4)]. In this concept, eight Yardney LR 85 cells, connected in series to produce 12 volts, were used to power an electrical-resistance-heated suit worn by the diver. The suit could also be powered by a power cable terminating in SEALAB II. This heater supplied 350 watts which was believed, at that time, to be sufficient. General conclusions were that the battery pack was too bulky and there were problems with hot spots in the electrical-resistance-wire suit.

HEAT OF SOLUTION

From September 1965 through June 1966, a timed heat-release chemical system was developed and tested by the Naval Missile Center in Point Mugu,

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[(4)] Frey, H. R., *Electrically-Heated Pressure-Compensated Wet Suits for SEALAB II*, Prepared for NMRI (Contract N600(168) 63855), National Naval Medical Center, January 1966.

California[5]. This system used the heat of solution of inorganic salts to produce heat. Compounds were developed to control the rate of heat release to the diver. The principal area of applications was the hands. It was calculated that 0.2 kilograms per hour of the compound would be necessary to keep both hands warm in 5°C water and it was demonstrated that 0.8 kilograms per hour of the compound was necessary in 0°C water. The specific weight of the mixture was about 1 gram per cubic centimetre, meaning volumes of 200 and 800 cubic centimetres per hour, respectively. These types of reactions which use seawater as a reactant appear ideal for heat sources, particularly in the case of spot heating critical areas such as the hands. Calcium chloride was chosen at the time as the most desirable salt for this system for a variety of reasons, but calcium chloride produces less heat on a weight and volume basis than other chemicals and if some other potential compounds could be made to work in a similar fashion, a several-fold increase in power could be obtained with the same volume of material. This area should be examined further for diver heating application.

ISOTOPIC HEATER

The next major development was the isotopic diver heater developed by Mound Laboratory in 1967-68 for the Navy's SEALAB III experiment[6]. This heater produced approximately 270 watts. The Naval Medical Research Institute (NMRI) calculated that it would require 450 watts at the surface and 1000 to 1200 watts at a depth of 183 metres to keep the diver warm with the suit configuration used (two 3/16-inch wet suits worn over the hot water tube suit[7][8]. The heat production was insufficient, and the overall weight and size too cumbersome for the diver. Additional heat capacity would only make it more cumbersome.

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[5] Naval Missile Center TM-67-1, *Timed Heat-Release Chemical System for Underwater Applications,* by K. N. Tinklepaugh and C. J. Crowell, 20 February 1967.

[6] Civil Engineering Laboratory Tech Note N-1087, *SEALAB III - Diver's Isotopic Swim Suit Heater System,* by J. J. Bayles and D. Taylor, May 1970.

[7] NMRI ltr NMRI-021-1p Ser 12584 (26 Feb 1969) to Naval Facilities Engineering Command (materials rearranged).

[8] Rawlins, J. S. P. and Tauber, J. R., Paper, *Thermal Balance at Depth,* (Undated but Printed about Mid-1969) Environmental Stress Div., NMRI, Bethesda, MD.

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METAL COMBUSTION HEATERS

In November 1968 the Naval Coastal Systems Center (NCSC), then the U.S. Navy Mine Defense Laboratory, issued a request for proposals through the Commerce Business Daily for a 1000-watt, 6-hour heat source for free swimming divers. As a result of this effort, the CONOX heater was developed by the General Electric Company for the Navy. This heater was designed to burn magnesium chips and oxygen at high temperatures. Tests were also conducted using iron and zirconium, but the magnesium seemed to work best. The heater worked well, but there were minor control problems. furthermore, the weight (15.9 kilograms without oxygen bottle and 21.3 kilograms with) and size of the heater system were somewhat excessive.

ELECTRICAL/HEAT OF FUSION AND SENSIBLE HEAT

Concurrent with the development of the CONOX heater, Sanders Nuclear Corporation developed a diver suit heating unit for the Navy using topside electrical power to heat water in a heater worn on the diver's back. This heater had its own pumping system which pumped the heated water through the tube suit worn by the diver. The thermal output to the diver was 845 watts in 21.1°C water, 685 watts in 10°C water, and 605 watts in -1.1°C water[9]. The heater worked well in this tethered mode. The heater contained a minimal amount of lithium hydride which acted as a heat capacitor to store heat for use by a free swimming diver. In this mode, electrical power would be used to melt the lithium hydride just prior to the dive and as the lithium hydride cooled, the heat of fusion and the sensible heat would be used to heat the diver. The amount of lithium hydride contained in this prototype was insufficient for long term missions, but it did demonstrate the feasibility of this concept. The concept might be particularly attractive if thermochemical "heat sticks" such as thermit were used periodically to regenerate the heater by melting the lithium hydride. For a single melt of the lithium hydride, allowing the lithium hydride to cool to 315°C from its molten state at 688°C, it was calculated that 2.3 kilograms of lithium hydride occupying approximately 4100 cubic centimetres (including expansion space) would be required for a 3 kW-hour mission. Further investigation will be necessary to determine if this concept is practical for diver use.

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[9] Naval Ship Research and Development Laboratory Informal Report, *Test and Evaluation of Diver Suit Heating Unit,* by H. S. Butler, Jr., September 1971.

MAGNESIUM-IRON-SEAWATER BATTERY

During the early 1970's, the Naval Civil Engineering Laboratory developed a magnesium-iron-seawater battery for diver heating[10]. This heat source is essentially a short-circuited magnesium seawater battery. Magnesium normally reacts with seawater to produce heat, but the reaction proceeds too slowly for the heat to be usable. The reaction becomes much more rapid when the magnesium is connected to iron electrically. The initial heater was designed to produce 2000 watts for 8 hours. In two tests, the heater produced in excess of 2000 watts for periods of 6 and 7 1/2 hours. The system weighed 17.7 kilograms and occupied a volume of 18,000 cubic centimetres.

After successful bench tests of the 2000-watt, 8-hour heater, a diver-carried heater was developed and tested[1]. The specifications on this heater were 1000 watts of heat for 8 hours. The weight of the heater was 15.4 kilograms and the overall volume was approximately 16,400 cubic centimetres. This heater was integrated with a hot water tube suit worn inside of the dry suit at the Naval Coastal Systems Center in May 1975. A diver spent 8 hours in near $0^{\circ}C$ water with this heater and suit arrangement and was considered to be in a thermally stable condition as evidenced by the rectal temperature. It was concluded that this type of heater should be practical for free swimming divers or tethered divers in certain applications, and could also be used as an emergency heat source on submersibles. As stated earlier, portable commercial heat sources based on the Navy's development of this concept are now available from Sea Systems Development and Kinergetics, Incorporated.

Additional development of the magnesium-iron-seawater heater was conducted in an effort to make the heater system more efficient and more controllable. Magnesium and iron plates used in the original heaters were replaced by magnesium-iron powder bonded together by ball milling the two components to produce micro-galvanic cells. Although the specific heat output of the powder was less than the dual plate cells used in other heaters, an inert slurry of the powder was developed which might be used in a more controllable reaction. Additional information on the ball milled powders is given in Reference 11.

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[1] ibid.

[10] Civil Engineering Laboratory Tech Note N1315, *Preliminary Development of an Electro-Chemical Heat Source for Military Diver Heating,* by S. A. Black and L. W. Tucker, November 1973.

[11] Civil Engineering Laboratory Technical Memo No. M-43-78-02, *Development and Evaluation of Supercorroding Alloys,* by S. A. Black and S. S. Sergev, November 1977.

The changing attitude of the diver (and heater) creates such problems with the magnesium-iron-seawater heater that it cannot presently be used by a nonstationary diver or vehicle. The heater vents hydrogen during the reaction which presents unique venting problems so it is unsuitable in this configuration for use in most free swimming or tethered diving operations. Attempts were made to operate the magnesium-iron-seawater heater in a pressurized vessel by letting the reaction "stew in its own juices" and allowing the hydrogen pressure to build up. These attempts were not successful because the reaction products, principally the magnesium hydroxide, tended to kill the reaction thereby reducing the efficiency beyond feasibility. Other heating techniques were then sought which might be more applicable to most Navy diving missions.

ADDITIONAL METAL COMBUSTION HEATERS

When the hydrogen venting problems on the magnesium-iron-seawater heater could not be easily solved, Navy researchers began looking at all potential heat sources which might be applicable for Navy missions. It appeared that the CONOX heater concept, based on the controlled combustion of magnesium chips with oxygen, might be well suited for these missions since (1) there is no gassing from the reaction, (2) the only by-product is a solid magnesium oxide ash, and (3) there is substantial energy released per unit weight and volume. Earlier efforts had demonstrated feasibility of this concept and only minimal development effort was required. On this basis, the Civil Engineering Laboratory entered into a contract with the Naval Coastal Systems Center in 1977-78 to refurbish the original CONOX heater, making any minor modifications necessary to put it in operable condition. This heater is operated by purging the combustion chamber with oxygen, igniting the magnesium chips, and regulating the oxygen supply to control the heat output after the initial combustion. Because the magnesium chips have a relatively high ignition temperature ($\approx 500^{\circ}C$), they require a significant amount of energy for ignition. To ignite the magnesium, a small electrically actuated ignition primer is used. The igniter contains 100 milligrams of primer material and requires 3 amps to activate. The primer ignites a thin cylinder of steel wool in the middle of the combustion chamber and the burning steel ignites the magnesium. Since the only gas in the combustion chamber is oxygen, the combustion occurs at pressures of less than 1 atmosphere (about 0.1 atm). The combustion is controlled using an absolute pressure regulator manufactured by Lif-O-Gen, Inc., downstream of the 205-atmosphere oxygen bottle and upstream of the orifice block leading to the combustion chamber. The orifice block has a constant upstream pressure of 2 atmospheres absolute (the set point of the regulator) and a constant downstream pressure of about 0.1 atmosphere. To change the power output, a different orifice is selected for the desired power level. The oxygen passes through a filter before entering the

regulator to prevent any foreign matter from blocking the regulator or orifices. There are numerous safety relief valves and a gas surge valve for diver safety in the event of failure of the regulator or other components in the gas supply system.

The reburbished heater was delivered to NCSC in mid-1978 where it was tested at the surface for a wide range of operating conditions. The heater was designed to produce 6 kW-hours of energy on a 0.9 kilogram charge of magnesium. In typical testing of the power-time relationships, 5 kW-hours of energy were obtained consistently from the heater for power ranges from 0.4 to 2.0 kW for durations from 12 to 2.5 hours, respectively. An engineering prototype heater based on this concept is currently being developed at NCSC. This prototype is designed to produce 3 kW-hours of energy in power output levels of 300, 500, and 1000 watts for 10, 6, and 3 hours. Total weight of the system, including the oxygen bottle, should be approximately 9 kilograms and the overall package will be approximately 38 by 25 by 13 centimetres.

PROPANE CATALYTIC HEATER

Concurrent with the refurbishment of the CONOX heater, NCSC contracted with Energy Systems Corporation (ESC) to develop a propane catalytic heater for use by divers. ESC had previously developed a unique propane catalytic heater system for use by downed aircraft pilots in extreme surface environments. They successfully demonstrated, under contract, that this concept was feasible for underwater use as well. As a result of the feasibility testing, ESC built five prototype propane catalytic heaters for use by the free swimming diver.

The prototype propane catalytic heaters were designed to produce a minimum of 500 watts for a duration of 2 1/2 hours using a 0.17 kilogram propane fuel canister. The units, as built, weigh 6.6 kilograms and displace 4500 cubic centimetres. They are 11.4 centimetres in diameter by 53.3 centimetres long. The heaters operate by burning propane in air (either surface supplied or from scuba bottles) over a catalyst bed in a controlled combustion reaction. Pressurized air from the first stage of a scuba regulator acts on a diaphragm to release the propane from the fuel cylinder where it is stored under its own vapor pressure (8.5 atmospheres absolute at 21.1^{o}C). The propane and air then travel through separate orifices to the catalyst bed-combustion chamber where they are ignited by an electrical spark generated by a peizoelectric igniter which also provides a restart capability. Once ignited, the heat of reaction sustains the combustion. The combustion chamber is water-jacketed with thermoelectric modules sandwiched in between. The thermoelectric modules convert part of the heat from the combustion chamber into electrical energy to drive a small pump which circulates 1.1 to 1.9 litres per minute of water through the water-jacket. This

warm water is then sent to the diver where it can be used to flush a wet suit or used in a closed-circuit mode using a heat distribution garment inside of a dry suit. Due to the small temperature rise (approximately 3^{o} to $4^{o}C$) of the water per pass through the heater, the closed-circuit mode appears far more practical.

ESC delivered the propane heaters to NCSC in September 1977. Unmanned testing by NCSC revealed the heaters would deliver the specified output of 500 watts for 2 1/2 hours. Manned testing was also conducted and subjective results were obtained. Ignition problems were evident in these prototypes which were attributed to improper fuel-air mixtures. It was also apparent that design improvements were required to overcome excessive heat loss to the environment and an an inherent protection system was necessary to prevent overheating in the event that the operator failed to follow the standard operating procedures. In addition, the amount of air reuquired (14 standard litres per minute) seemed quite excessive from a storage standpoint for a free-swimming diver.

Based on this analysis, ESC performed additional work on contract. The starting problems were overcome by a redesign of the fuel-air mixture system. ESC also conducted some research to determine the feasibility of using oxygen instead of air as the oxidizer, thus reducing the storage requirements by a factor of five. Their research indicated that there was no simple way to obtain a controlled catalytic combustion using oxygen and propane. Based on the results of this study, it appeared that the prototype heaters required too much storage space for the oxidizer for most Navy scuba diving missions and that this concept might be better suited for surface-supported diving missions in which the air could be supplied to the heater via a small diameter umbilical.

On this basis, ESC contracted to build a propane catalytic heater using surface-supplied air, which would have higher heat output capabilities and longer duration than the scuba units, and would incorporate design improvements to correct the deficiencies in the prototype heaters. The surface-supported propane catalytic heater should produce approximately 100 to 750 watts of heating power for durations from 4 hours at 750 watts to 9 hours at 350 watts. The heater will use a standard 0.46 kilogram propane cylinder. Once these units are developed, it is anticipated that research will be conducted towards using these heaters at extended depths. The current heaters are dependent on the driving pressure of the propane vapor to supply the fuel. The heaters will be limited to an operational depth of approximately 61 metres at a fuel canister temperature of $21.1^{o}C$ and lesser depths for colder fuel temperatures. Currently, the combustion exhaust gases are used to heat the fuel canister before leaving the heater. For depths in excess of 61 metres, it may be necessary to heat the fuel to higher temperatures or use a fuel such as ethylene with a higher vapor pressure curve than propane.

HYDRAULIC HEATER CONCEPT

In 1977, the Navy became interested in a heating concept proposed by Westinghouse Electric Corporation, Oceanic Division, for heating a personnel transfer capsule or a surface-supported diver. In this concept, high pressure water at ambient temperature is pumped to the PTC or to the diver where the fluid power is converted into heat using a hydraulic heating device. This process eliminates most of the high hose heat losses encountered in typical surface-supplied hot water heating systems. Westinghouse contracted to further explore the feasibility of hydraulic heating devices by constructing two separate heaters—one designed for high efficiency for greater heat outputs such as those required for PTC heating and a smaller diver-carried device with less efficiency but more compact designed for use by a single diver. Both units were built and successfully demonstrated during FY 1978.

For the high efficiency hydraulic heater, high pressure water from the surface is used to drive a reciprocating cylinder motor which powers a reciprocating cylinder pump. The reciprocating pump circulates water in a secondary loop through a high pressure restriction where the fluid power is converted to heat due to friction. The overall size of the prototype unit is about 12.7 centimetres wide, 20.3 centimetres high, and 48.3 centimetres long. The weight is about 37 kilograms. Tests were conducted at Westinghouse on the high efficiency heater for surface conditions using fresh water in both the primary and secondary loops. A 5.6 kilowatt electric motor was used to drive a high pressure positive displacement pump similar to those used in coin operated car washes. At a maximum operating pressure of 137 atmospheres absolute, the pump delivered approximately 22.7 litres of water per minute to the efficient hydraulic heater. This corresponds to a fluid power input of 4.9 kilowatts. The heater produced 4.1 kilowatts with a heating efficiency of 84 percent. This and other results indicate that hydraulic heating can be highly efficient and may be quite feasible for supplying large amounts of heat where the overall size and weight is not as limiting a factor such as for PTC application. Furthermore, it is anticipated that for these applications, the use of titanium rather than stainless steel as used in this prototype could reduce the overall weight to less than 18 kilograms, making the high efficiency hydraulic heater even more attractive.

For the smaller diver-carried hydraulic heater, the same source of high pressure water used with the efficient hydraulic heater is used to drive a small impulse turbine-centrifugal pump combination which converts the fluid power to thermal energy through friction in the pump and through forcing the water from the pump in the secondary loop through a high pressure restriction. The overall size of the small, less efficient hydraulic heater is 5.7 by 5.7 by 8 centimetres and weighs 1.4 kilograms.

Test results show that for a water input of 21.95 litres per minute at a pressure of 134.3 atmospheres absolute to the turbine-pump combination, the turbine rotates at approximately 55,000 revolutions per minute producing 2.32 kilowatts of thermal energy in the secondary water loop. This corresponds to a heating efficiency of 47 percent of the 4.98 kilowatt supply fluid power. Again, these tests were conducted at the surface using fresh water in both the water supply loop to the turbine and the secondary loop used to simulate a diver's heat load requirements. Considering the overall size and performance of this small diver-carried hydraulic heater, the concept is very attractive for diver heating if it can be adapted for salt water use.

Of the two different hydraulic heater types built and tested, the small diver-carried unit is applicable to more Navy missions so the Navy is continuing the development of that heater to further establish the practicality of its use. Westinghouse is presently under contract to conduct the additional design analyses required for adapting the current design for salt water use and the further modifications required to go from a prototype breadboard version to an engineering model for manned testing by divers in an underwater application. Should these design analyses indicate the practicality of this concept, the next logical step is the construction of the engineering model. Additional design information and test results on both prototype hydraulic heaters is given in Reference 12.

OTHER HEATER CONCEPTS

In addition to the major heater developments described, the Navy has also investigated numerous other heating techniques on a more minor scale. Most of these were in the area of diver breath heating techniques and included studies of the vortex tube, hydrogen-oxygen catalytic heating, thermit (aluminum and iron oxide), and standard hot water-supplied breath heaters. Gloves were also tested which used heat from crystallization material to warm the hands.

The vortex tube is a commercial device which separates compressed gas at ambient temperature into a hot gas stream and a cold gas stream at a reduced pressure. Tests were conducted at NCSC to determine the feasibility of using this device for heating a diver's breath or for spot heating such crucial areas as the hands and feet[(13)]. It was

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[(12)] Westinghouse Electric Corporation, Oceanic Engineering Report 78-31, *Breadboard Hydraulic Heaters,* by J. R. Colston and G. E. Chetta, 31 August 1978.

[(13)] Naval Coastal Systems Center Informal Report, *Vortex Tube Test Report,* by B. E. Miller, July 1977.

concluded that this device could provide 90 to 150 watts of heat at depths of 91 metres for overbottom pressure on the order of 8.2 atmospheres and gas flow rates on the order of 28.3 actual litres per minute. It was concluded that this device was not very feasible for breath heating when comparing the overall net heat produced, the control system requirements, and the excessive gas consumption costs when using heliox (a given volume of heated gas is obtained at the expense of discharging a comparable amount of cold gas). It could be used for purging a diver's dry suit with warm air as they become chilled or for spot heating of the hands and feet.

The Foundation for Ocean Research has developed and patented a device for heating and humidifying the breathing gas through the catalytic burning of hydrogen and oxygen. This device mixes a small amount of hydrogen (approximately 1.0 to 1.3 percent) in the breathing air and as the air passes over a catalyst bed the hydrogen burns with the oxygen to form water vapor and excess heat which warms the breathing gas. NCSC funded the Foundation for Ocean Research to study this concept and provide a test and evaluation report on the applicability of this device[(14)]. Simple quantitative body temperature measurements with and without the heater at shallow depths were inconclusive in demonstrating the value of this device. However, subjective analysis by the divers indicated it to be highly desirable in the chilly waters off San Diego. The device appears to be marginal for the breath heating requirements for saturation diving on heliox.

A third type of breath heater tested by NCSC was developed by Thermology, Inc., of Elm Grove, Wisconsin. This heater uses thermit cartridges to heat a heat capacitor which warms the diver's breath. Thermit is a mixture of aluminum and iron oxide which produces heat at high ignition temperatures where the aluminum burns to form aluminum oxide by robbing the oxygen from the iron oxide. The thermit is ignited by a primer charge and the combustion is quite rapid necessitating a heat capacitor for the slower release of the heat to the breathing gas as required. The heater uses cartridges about the size of a .410 gauge shotgun shell and has overall dimensions of 8.9 centimetres diameter by 33 centimetres long. Test results indicated that each cartridge produced approximately 15 watt-hours of heat. This is insufficient thermal energy for extreme breath heating requirements such as for saturation diving.

NCSC has also evaluated the more conventional means of breath heating using hot water to heat the gas in a water-to-gas heat exchanger. Commercially available units and units designed and built by NCSC were

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[(14)] Foundation for Ocean Research NCSC Contract N61331-77-M-0549, *The Breath Heater and Humidifier for Breathing Apparatus, An Initial Test and Evaluation Report,* by S. E. Seuss and J. D. Isaacs, September 1972.

tested for both unmanned and manned conditions to depths of 610 and 381 metres on heliox[15][16]. Indications were that the Kinergetics breath heaters performed well under these conditions producing a 27.8°C rise in temperature for an inlet gas temperature of 7.2°C. However, up to 40 percent of the heat was lost from the heat exchanger to the diver's mouth through the hose and associated fluid passageways (sideblock) on the bandmasks used in the tests. This indicated that while the heat exchangers performed quite well, better insulation is needed on the equipment downstream or supplementary heat might be required in heating the sideblock to obtain maximum effectiveness from the heat exchangers.

Another concept evaluated by NCSC was a heated glove developed by Diving Unlimited International. This glove has pockets in it which contain a super saturated solution of certain inorganic salts which upon activation release the latent heat of crystallization as the liquid solidifies . This concept is attractive because the heat is released at a constant temperature which is selected by adjusting the mixture of the salts to obtain the desired melting temperature. In tests, these gloves were adequate for warming the diver's hands in cold water for short periods.

SUMMARY

Table 8 summarizes the physical characteristics of the heater concepts examined in the Navy's underwater heater development efforts.

AREAS FOR FUTURE DEVELOPMENT

The Navy is continuing development of the magnesium-oxygen combustion heater, the propane-air catalytic heater, and the hydraulic seawater heater because these concepts should provide both feasible and practical means for extending the mission capabilities of the Fleet diver. The magnesium-iron-seawater heater, whose initial development was conducted by the Navy, is being developed by commercial firms and could be of great interest should the problems associated with hydrogen venting for changing diver orientation be overcome (perhaps by burning the vented hydrogen with oxygen in a secondary heat producing reaction). Of the other potential heat sources considered, those which may show the greatest promise are (1) the hydrocarbon-oxygen catalytic heater; (2) the hydrogen-oxygen

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(15)Naval Coastal Systems Laboratory Technical Memorandum 206-77, *Breathing Gas Heater Test Results,* by B. E. Miller, October 1977.

(16)Naval Experimental Diving Unit, Panama City, Florida NEDU Report 9-78, *Evaluation of Kinergetics Breathing Gas Heater,* by J. R. Middleton and B. E. Miller, April 1978.

(Text Continued on Page 26)

TABLE 8

PHYSICAL CHARACTRRISTICS OF UNDERWATER

HEAT SOURCES INVESTIGATED BY THE NAVY

Heater Type	Status	Intended Application	Typical Thermal Output Power (Watts)	Typical Thermal Output Duration (Hours)	Size* (cm^3)	Weight (kg)
1. Electrical resistance	Working Model	Free Swimmer	350	3.0	8600	15.9
2. Heat of solution ($CaCl_2+H_2O$)	Working Model	Spot Heating (hands)	50-200/kg fuel	0.8/kg fuel	200/kg fuel	0.8/hr use
3. Isotopic heater	Working Model	Free Swimmer	270	Indefinite	18,100	28.3
4. Magnesium-oxygen-combustion						
Unit #1	Working Model	Free Swimmer	1000	5.0	20,000	21.3
Unit #2	Being Developed	Free Swimmer	500	6.0	12,300	9.0
5. Electrical/heat of fusion/sensible heat	Working Model	Tethered Diver	600**	Indefinite	10,300	11.3
6. Magnesium-iron seawater battery						
Unit #1	Working Model	Free Swimmer	2000	8.0	18,800	17.7
Unit #2	Working Model	Free Swimmer	1000	8.0	16,300	15.4
7. Propane-air catalytic						
Unit #1	Working model	Free Swimmer	500	2.5	14,000	20.0
Unit #2	Being Developed	Free Swimmer	750	4.0	10,000	10.0
8. Propane-oxygen catalytic	Feasibility Studies	Free Swimmer	-	-	-	-
9. Hydraulic heater						
Unit #1	Working Model	PTC	4000	Indefinite	12,500	37.0
Unit #2	Working Model	Tethered Diver	2000	Indefinite	300	1.5
10. Vortex tube	Working Model	Spot Heating (Breath, Hands)	150***	Indefinite	50	0.5
11. Hydrogen-oxygen-catalytic	Working Model	Breath Heating	200	1.0	125	2.5
12. Thermit	Working Model	Breath Heating	30	0.5	2000	2.5
13. Heat of crystallization	Working Model	Hands Heating	80/Glove	0.5	300/Glove	0.7 kg/ Glove

*Includes oxidizer requirements for non-tethered systems.

**In the electrically heated mode for a water temperature of -1.1°C.

***At an overbottom pressure of 8.2 atmospheres.

catalytic heater; (3) concepts using the latent heat of fusion and sensible heat from a stored heat source; (4) concepts using the heat producing reactions of different compounds with seawater, thereby eliminating oxidizer storage requirements; and (5) the vortex tube for spot heating applications such as the hands.

The storage requirements for air in the propane-air catalytic heater make this concept marginal for use by the free swimmer. Should a technique be developed to burn hydrocarbons such as propane catalytically with oxygen in a controlled fashion, this heater concept could become an attractive solution for certain diver heating applications. For a 3 kW-hour mission, a total system volume of approximately 10,000 cm^3 would be required with a total system weight of 8 kilograms. Even more ideal would be a propane heater using the diver's exhaust gas as an oxidizer. The diver's exhaust gas contains more than enough oxygen to burn the propane at a 500-watt rate and, if feasible means could be developed to recover this breathing gas, the overall volume could be reduced to one-half the size of a propane-oxygen catalytic heater.

The hydrogen-oxygen catalytic heater concept has thus far only been tried in breath heating applications but could perhaps be more useful in a system for totally heating the diver. Again, the major problem is controlling the combustion of hydrogen and oxygen in the mixtures required to produce heat outputs on the order of 500 to 1000 watts. Should a technique be developed for burning hydrogen catalytically with oxygen in stoichiometric proportions in a controllable combustion reaction, a total system volume of as little as 6000 cm^3 and a total system weight of approximately 10 kilograms could be achieved for a 3 kW-hour mission if the hydrogen is stored as a metal hydride.

Using stored heat such as that available as sensible heat and heat of fusion in a heated liquid is particularly attractive for free swimmer applications because the system becomes so simple. The diver is not dependent on the completion of chemical reactions, maintaining high combustion temperatures, or relying on mechanical or electrical systems. The major concern for free swimmer heating is getting maximum heat storage with minimum volume and weight with the heat available at a temperature the diver can use. Because the diver is dependent on the amount of heat stored at the beginning of the mission and cannot generate additional heat, particular attention must be given to insulation.

High temperature storage is necessary to obtain maximum heating for a minimum volume of weight, so special emphasis must also be given to the proper design of the heat capacitor and distributor system for providing the diver's thermal requirements safely. Provided these problems can be overcome, lithium hydride looks particularly attractive for this application. If lithium hydride is allowed to cool from a solid at its melting temperature of 688°C to a liquid at a temperature of 25°C, approximately

1820 watt-hours of heat are released per kilogram of material. This means that roughly 1.65 kilograms of lithium hydride, when initially heated above its melting temperature, could store enough heat for a 3 kW-hour mission. If it is assumed that 50 percent of the heat is lost to the ambient surroundings, 3.3 kilograms would be sufficient. Without allowing for expansion, 3.3 kilograms of lithium hydride would occupy about 2600 cubic centimetres. The insulation and packaging of the lithium hydride could be accomplished within reasonable size and weight restraints which should make this concept quite promising from that standpoint as a small, reliable, portable diver heater. Such a device was proposed by Sanders Nuclear Corporation in 1968, but the concept was not explored to its full potential.

Another area worth further development is in the use of chemical reactions of compounds with seawater. The magnesium-iron-seawater reaction has been developed successfully for use as an underwater heater. Other reactions also appear promising, particularly the hydrolysis and hydration reactions. As stated earlier, some work has been conducted with calcium chloride, but there are other compounds whose reaction with seawater produces many times the amount of heat and these reactions should be examined further. They seem particularly adaptable for heating the diver's hands.

Finally, the studies conducted on the vortex tube indicate that, although it does not seem practical as a breath heating technique, it might be very useful for heating the diver's hands on an intermittent basis. As greater emphasis is placed on keeping the diver's hands warm for missions requiring good dexterity or tactile sensation, this concept might be readily adaptable since there is usually a source of compressed air available for diving missions.

There are probably numerous other heater concepts which have been examined or discussed by researchers, diving companies, and working divers that have not been mentioned here, yet may warrant further development. In this report, an attempt has been made to include a discussion of as many feasible concepts as possible, to describe some of the more major developments of some of these concepts by the Navy and its contractors, and to give some insight into those areas which might be promising for future development. While this report does not include examinations of all heater concepts, the information presented here should provide a basis of comparison when considering other heating concepts.